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CATHODIC PROTECTION CURRENT DEMAND OF VARIOUS ALLOYS IN SEA WATER

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ABSTRACT

The long term current demand can be useful when choosing the potential and determining the current output for a cathodic protection system. The current demand of various copper based, aluminum, titanium, stainless, monel, and mild steel alloys at potentials between -0.6V and -1.1V (vs Ag/AgCl) has been monitored for over 800 days. The lowest current densities for most alloys were obtained at -1.0V.

The influence of factors such as oxygen level, fouling, and the formation of cathodic film on the current demand have been determined. This investigation was carried out on a state-of-the-art potentiostat designed in-house. This potentiostat can monitor the current demand of up to ten specimens at each of six potentials.

INTRODUCTION

Cathodic protection, either by impressed current or galvanic anodes, is now used to protect a great many structures in the marine environment. In particular, all of the ships in the Canadian Navy have some form of cathodic protection on the underwater hull. Similarly, other seagoing vessels and marine structures also require cathodic protection both internally and externally to prevent corrosion.

In the Canadian Navy galvanic zinc anodes are normally used on smaller vessels because these anodes are self-regulating, i.e. they supply only sufficient current to protect bare areas and do not require continuous monitoring as some impressed current systems do. Zinc anodes will produce a maximum negative potential of -1.0V (Ag/AgCl).

Impressed current cathodic protection systems are used on larger vessels and have the advantage that they can be set at any potential more negative than the corrosion potential of the metal to be protected. Impressed current systems are cheaper in the long term, the anodes and electronics will last the life of the vessel, can easily be designed to be self-regulating (i.e. maintain a set

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potential and increase current output as required), and require little human monitoring. An increase in current demand with time can be used as an indication that there is damage and deterioration of the underwater paint system, and remedial action can be initiated.

When impressed current cathodic protection systems were first installed on Canadian Naval vessels a potential of -0.85V (vs Ag/AgCl) was used. This potential was chosen because it gave adequate protection against corrosion of the steel hull and did not damage the underwater paint system. With the advent of advanced underwater paint systems (prganometal polymers), which are tolerant of more negative potentials, -0.85V may not be the ideal cathodic protection potential. One of the objectives of this research program is to determine whether other potentials would give better and more economical protection.

Several international organizations (NACE, Norwegian TNA, and UK Dept. of Energy) concerned with corrosion prevention and cathodic protection have prepared recommended practices for cathodic protection requirements. Using a design criteria current density of 80-160 mA/m^2 for bare steel they recommend that a minimum cathodic protection potential of -0.8V be maintained.[1]

When designing a cathodic protection system for a ship's hull or other marine structure, information on the relationship between the choice of cathodic protection potential and current requirements to maintain that potential is necessary. Data of this nature is presently not available. In a recent paper Scully and Hack[2] have investigated galvanic corrosion of various alloy couples using long term (120 days) and short term (one hour) potentiostatic polarization studies. This has allowed them to predict the corrosion behaviour of some bimetal couples in sea water. However, long term current demand data for single alloys are not available. Another purpose of this study was to investigate the current demand of metals at various potentials over an extended period of time.

The long term (800 days) current demand of several copper, aluminum, titanium, stainless and ferrous alloys has been monitored and analyzed. The influence of oxygen level (seasonal and daily) and fouling on current demand have also been monitored.

EXPERIMENTAL

The current demand of the alloys listed in Table I have been investigated in this study.

The sea water used for these experiments was pumped directly from the ocean to the laboratory using only a coarse strainer to protect the pump impellor. The laboratory is fed by a system using dual sea water intakes which are alternated monthly to prevent accumulation of fouling in the sea water lines.

The experiment was carried out twice, once between 1973 and 1980 (2000 days), and restarted in 1983 using a more accurate monitoring system, and continued for over 800 days. The 2000-day and 800-day data were similar and for clarity only the 800-day data are presented in this paper. All experiments were carried out in slowly flowing sea water in a laboratory tank, and panels were held at potentials between -600 mV and -1100 mV versus a Ag/AgCl reference electrode. All alloy panels (one panel of each alloy at each potential) 7.6 cm x 10 cm x 3.2 mm were grit blasted with 100 mesh alundum immediately before immersion. The data for these experiments were initially recorded daily but after three months, data were recorded weekly. The data were then transferred to a computer and plotted as current demand versus time.

Although standard potentiostats (normally used in potentiostatic polarization studies) could have been used to monitor current and voltage, they are normally only designed to monitor one specimen at a time. To monitor up to sixty panels for several years would require many conventional potentiostats. Two different devices were designed in-house that can maintain up to ten panels

at each fixed potential and allow monitoring of the current demand.[3]

For the first series of tests, a simple potentiostat was designed at DREP (state-of-the-art at the time, 1973) that allowed the monitoring of up to ten panels at one potential. One such set up, consisting of a power supply, electronic circuits, and a car battery at each potential. An electrical diagram of the potentiostat is shown in Figure 1. This early design required that the current be measured as a potential drop across a 0.1 ohm resistor (using Ohm's Law). This technique was intrusive and at low potential, drops could result in significant errors in the current calculation. A second potentiostat was designed to avoid this intrusion, to simplify the electronics and to reduce the number of power supplies required.

This second, more efficient system, using the present state-of-the-art electronic design, was designed in-house three years ago and more detailed information is available in Reference 3. The device can potentiostatically control up to sixty panels (cathodes) at up to twelve different set potentials in minimum blocks of five panels per set potential. The current demand of individual panels can be displayed on a front panel digital meter using two rotary switches. The system can supply up to 200 mA of current per panel, for a total of 12A. In the new design the cathode is ungrounded and draws the current from a fixed potential anode. A block diagram of the new design in shown in Figure 2. This system has a car battery as a backup power supply in case of a power failure.

EXPERIMENTAL LIMITATIONS

Temperature, salinity, and oxygen concentration of the sea water are controlling factors that determine current density requirements. With temperature and salinity relatively constant (32,000 ppm - winter, 30,000 ppm - summer) throughout the experiment. The sea water salinity in this area of the northeast Pacific is lower than that of typical open ocean seawater (35,000 ppm). It is the oxygen concentration and the cathodic deposits formed during the reduction of oxygen that are major factors affecting the current density.

At a potential more positive than -1.1V the following reactions occur at the surface of the cathode (metal alloy);

$$2H_2O \rightarrow 2H^+ + 2OH^- \quad (1)$$

$$2H^+ + 2e^- \rightarrow 2H \quad (2)$$

$$2H + 1/2O_2 \rightarrow H_2O \quad (3)$$

The overall reaction is:

$$H_2O + 1/2O_2 + 2e^- \rightarrow 2OH^- \quad (4)$$

Reduction of oxygen at the cathode prevents corrosion and the concentration of oxygen at the cathode surface determines the current requirement. It is the formation of the alkali (OH^-), reactions (1) and (4), at the surface of the cathode which results in the formation of a cathodic deposit. No attempt was made to study the composition of the cathodic deposit on the various alloys at different potentials. Some attempts have been made to monitor the formation of the cathodic film[4-6], but more work is required in this area. Further work on cathodic films has been initiated in this laboratory.

At potentials more negative than -1.1V, reaction (5) occurs at the cathode and oxygen is not a controlling factor in this reaction. The current demand is now controlled mainly by the resistance of the sea water (temperature and salinity dependent) and, as it forms, the cathodic film generated by the alkali at the surface.

$$H_2O + e^- \rightarrow 1/2H_2 + OH^- \quad (5)$$

Although it is the average long term current requirement that is the major concern in this paper, factors that influence the concentration of oxygen in the sea water will have a significant effect on the daily variations in the current demand.

In choosing to carry out the experiment in fresh flowing sea water, allowing data to be gathered in a

realistic environment, day-to-day variations in the oxygen level were difficult to control. Most of these are external factors and will be discussed before presenting full experimental results.

The oxygen level of sea water varies with the time of day. In a previous experiment, the current demand and oxygen concentration were monitored continuously over a three-month period, May-July 1976, for a mild steel panel held at -1.0V. Figure 3 shows the variation of oxygen level during several 24-hour periods. Both the oxygen level and current demand are at their lowest point around 0500-0600 hours and reach a peak at 1500-1700 hours. These correspond to low and high points in the daily photosynthesis cycle (sunlight and biological oxygen generating processes in the sea water).

Weather can also affect the daily oxygen cycle, lower oxygen concentrations were observed on cloudy days, with a subsequent reduction in the current demand. Seasonal variations in the oxygen level were relatively small (0.55-0.6 milliequivalents/litre) and no seasonal variation could be observed in the recorded data.

Sea water temperature is another factor that can influence the oxygen level and thus the current demand. Seasonal variations in the sea water temperatures in the northeast Pacific are small (9 ±3°C) so this was not an important factor in this study.

Interruptions in the sea water flow due to technical problems with the pumping system or the necessity of changing pumps for maintenance reduces the oxygen level in the tank and reduces the current demand of the panels for a short period of time but does not affect the long term data.

Fouling of the panel surface with barnacles and tubeworms reduces the effective area of the panel and thus affects the current density calculation. Fouling can be controlled or eliminated for the first year or two by starting the experiments in the summer after the attachment period of the barnacle is over. In some instances, fouling has fallen off the panels during tank cleaning, resulting in increased current density (spikes in some of the graphs). Overall fouling was the same for all alloys and, over the length of the experiment, has the same relative effect on the current demand on each of the alloys. The toxic nature of the alloys did not reduce the fouling as cathodic protection reduces the leaching of toxic metal ions to virtually zero. Removal of the fouling was not practical because of the damage that would occur to the surface film. An example of the extent of the fouling is shown in Figure 4.

Cleaning of the tank to remove accumulated silt and debris brought in by the pump also affects the current reading. During cleaning, silt can be deposited on the surface of the panels. This effectively reduces the surface area and could damage the cathodic film especially on panels held at the lower potentials. This damage is small and over the long term does not affect the data.

All of these factors are responsible for the "noise" or fluctuations seen in the long-term current demand plots. Although these factors affect the day-to-day data, over the long term they are averaged out, allowing one to estimate a value for the long term current demand.

RESULTS

The current density data for each of the alloys are presented graphically in Figures 5-14.

For the trends in the data to be more apparent, the data have been broken down as follows:

a) The total current requirement for each alloy at each potential has been calculated (this is the equivalent to the area under the curve) for three time periods, 0-50 days, 0-100 days, and 0-800 days (Table II). These data are also presented graphically in Figures 15-19.

b) The average of the current density

for each alloy has been calculated for the same 4 time periods, and the final 12 weeks (Table III).

The total current density and the average current density for all alloys have been calculated and are plotted in Figures 18 and 19 and tabulated in Tables II and III.

General Observations

Potentials of -0.6V and -0.7V Although this is not a potential normally used for cathodic protection, it is the potential range obtained when steel anodes are used to protect copper based alloys, especially in sea water condenser/evaporator systems. At these two potentials the current demand was very erratic making it difficult to obtain an average current density with any accuracy but was much higher than at other potentials. Polarization occurs in the first fifty days and there is not much change in the current demand after this initial polarization.

Potentials of -0.8V and -0.9V This is the range of potentials currently used to protect Canadian Naval vessels (-0.85V). For most alloys there is some polarization in the first week or two and then the current demand settles to a steady level with very little change over time. The fluctuations in current demand are much smaller than those seen at -0.6V and -0.7V.

Potential of -1.0V This is the potential associated with cathodic protection with zinc anodes. All of the alloys were polarized within 50 days to within 20% of the final average current demand. Monel, mild steel, and 316 stainless steel alloys continued to drop in current demand with time while the other alloys reached a constant current demand level after 100 days similar to that after 800 days.

Potential of -1.1V The copper based, aluminum, and titanium alloys polarized rapidly to a level close to the average long term current demand, which was similar to the average long term current demand level at -1.0V. Monel, mild steel, and 316 stainless steel took considerably longer to polarize (150-200 days) than the other alloys and the final average current demand was much higher than at -1.0V.

DISCUSSION

Formation of Cathodic Films

Neglecting the data at -1.1V, there are some general trends evident in the data. All of the alloys showed a similar trend to lower average current densities as the potential became more negative. Correspondingly, the total current densities decreased as the potential is lowered (Tables II and III). Although there are some variations in current density requirements with alloy composition, for practical applications the current density could be considered independant of the alloy composition at any given potential. The average long term current density for all alloys could be used to set design criteria, especially for mixed alloy systems (Tables II and III and Figures 15-19).

The trend to lower current requirements at lower potentials is due to the formation of a cathodic film. This cathodic film, generally composed of $CaCO_3$, $MgCO_3$, and $Mg(OH)_2$, is formed on the surface due to the generation of alkali at the alloy surface during the reduction of oxygen (Equation 4). The natural carbonate/bicarbonate equilibrium in sea water (Equation 6) will be shifted to the left in the presence of excess alkali; the pH has been estimated at 11-12 at the alloy surface.[4] This produces higher concentrations of carbonate which then precipitates as calcium carbonate forming the cathodic film (Equation 7).

$$H_2O + CO_3^{-2} \rightarrow HCO_3^- + OH^- \quad (6)$$

$$Ca^{+2} + CO_3^{-2} \rightarrow CaCO_3 \quad (7)$$

In previous work on cathodic films on steel in sea water (100 hours exposure), it was found that the cathodic film formed at -1.03V was more protective than the one formed at -0.93V (i.e. reduced current demand at more negative potentials).[4] The composition, thickness, and texture of the cathodic

film was dependent on the potential of the alloy and the velocity of the sea water past the alloy. Similarly, a recent study of the cathodic protection of stainless steels[7] showed that lower current densities were required as the potential was changed from -0.3V to -0.9V. The current demand was independent of the alloy composition (Cr 18-27% and Ni 4-31%) of alloys with free corrosion potentials varying from +0.2V to -0.3V.

There is a wide divergence of the average current densities at -1.1V. Although the copper based, aluminum, and titanium alloys have reduced average current densities from -1.0V, mild steel, 316 stainless steel, and monel have much higher average long term current densities at -1.1V than at -1.0V. The reason for the difference between alloys has not been fully investigated, but is related to the hydrogen overpotential. At -1.1V the reaction occurring at the surface not only involves the reduction of oxygen (Equation 4) but also the electrolysis of water and production of hydrogen (Equation 5). The extent to which each reaction occurs is dependent on the alloy and its hydrogen overpotential. Further work will be carried out to study the cathodic films formed on the various alloys as a function of potential. If hydrogen is produced at the alloy surface, a more porous cathodic film could result, with a correspondingly increased current demand.

Choice of Design Cathodic Protection Potential and Current Density

The data clearly show that a potential of -1.0V requires the lowest average long term current demand. This is the ideal potential for cathodic protection of steel and stainless steel, and for practical purposes, most other alloys. Although the copper based, aluminum, and titanium alloys have a lower average current demand at -1.1V than at -1.0V, this potential is a poor choice, especially for coated alloys, because of the possibility of cathodic delamination of the coating.

In choosing a cathodic protection potential, the initial polarization current demand must also be taken into account. The higher initial average current density may require a power source that would be uneconomical at the lower average current densities after polarization. The average current density and the total current requirement for 0-50 and 0-100 days also indicates that a potential of -1.0V requires the least amount of current. During the initial polarization, -1.1V is also a poor choice because the initial current demand is higher than at -1.0V.

It is normal practice, especially for unpainted marine structures, to lower the potential of the structure slowly to the desired potential (usually more positive than -1.0V). This allows the use of smaller power supplies that will provide adequate power to maintain the chosen potential after the structure has been polarized, but not so small that polarization occurs too slowly. From the data presented, it appears that whatever decision is made on the size of the power supply, the sooner the potential is lowered to -1.0V the lower the current requirements will be.

At present Canadian Naval ships are cathodically protected at -0.85V. The number of anodes and choice of power supply was based on a current density criteria of 45-55 mA/m^2. This potential was chosen as a compromise because, at the time the cathodic protection system was designed, the underwater coating system was susceptible to cathodic delamination at -1.0V or more negative potentials. The present underwater paint systems have shown no blistering or copper conversion at -1.0V and in some cases down to -1.2V. As a result of this study, consideration will be given to increasing the cathodic protection potential to -1.0V, which is similar to the potential of a zinc anode. The current design criteria of 45-55 mA/m^2 could be reduced to 25-35 mA/m^2 due to the reduced current density requirements at -1.0V.

CONCLUSIONS

The potential that provides the most economic cathodic protection system, -1.0V would be the ideal potential of -1.0V as soon as possible on a

structure would also reduce the long term current requirements.

If -1.0V is chosen as the cathodic protection potential then a final current density criteria of 25-35 mA/m^2 would allow for the design of an adequate cathodic protection system.

In designing a cathodic protection system for a structure containing several alloys, the current requirement for practical purposes is independent of the alloy composition.

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3. G.K. Schattschneider, "Long Term Current Demand Control Device", Defence Research Establishment Pacific, Technical Memorandum 82-8, October 1982. (Canada, USA Patent Pending)

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5. W.H. Hartt and S.L. Wolfson, "An Initial Investigation of Calcareous Deposits Upon Cathodic Steel Surfaces in Sea Water", Corrosion/80, Paper No. 152, National Association of Corrosion Engineers, Chicago, 1980.

6. W.H. Hartt, C.H. Cuthbertson, and S.W. Smith, Corrosion, Vol. 40, No. 11, p. 609 (1984).

7. R. Johnsen and E.Bardal, Corrosion, Vol. 41, No. 5, p. 296 (1985).

TABLE I

Alloy Common Name	USN Designation
Aluminum bronze	C61300
Naval brass	C46400
Copper	C11000
90/10 Copper/Nickel	C70600
70/30 Copper/Nickel	C71500
Monel	N04400
316 Stainless Steel	S31600
Titanium	R50400
Aluminum	A96061
Mild steel	G10200

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TABLE II

Total Current Requirements

METAL	POTENTIAL	TOTAL CURRENT REQUIREMENT FOR $1m^2$ (Ampere-Day)		
	(volt)	50 days	100 days	800 days
ALUMINUM BRONZE	-0.6	16	26	132
	-0.7	12	18	72
	-0.8	7	14	81
	-0.9	5	9	70
	-1.0	4	7	51
	-1.1	8	11	26
BRASS	-0.6	12	20	115
	-0.7	10	15	76
	-0.8	9	15	75
	-0.9	9	13	50
	-1.0	8	12	49
	-1.1	5	8	30
COPPER	-0.6	14	23	107
	-0.7	11	16	79
	-0.8	6	11	66
	-0.9	5	8	57
	-1.0	4	6	39
	-1.1	9	12	24
90/10 COPPER/NICKEL	-0.6	13	21	99
	-0.7	11	16	94
	-0.8	5	9	65
	-0.9	3	6	52
	-1.0	4	7	29
	-1.1	10	14	32
70/30 COPPER NICKEL	-0.6	13	18	86
	-0.7	12	17	97
	-0.8	4	7	69
	-0.9	3	5	54
	-1.0	4	6	23
	-1.1	12	17	32
316 STAINLESS STEEL	-0.6	13	19	105
	-0.7	12	19	76
	-0.8	9	14	62
	-0.9	6	9	35
	-1.0	5	7	23
	-1.1	18	27	47

TABLE II
(cont)

Total Current Requirements

METAL	POTENTIAL	TOTAL CURRENT REQUIREMENT FOR $1m^2$ (Ampere-Day)		
	(volt)	50 days	100 days	800 days
MONEL	-0.6	13	21	118
	-0.7	11	17	91
	-0.8	5	8	65
	-0.9	4	6	69
	-1.0	5	8	21
	-1.1	26	27	47
TITANIUM	-0.6	11	17	119
	-0.7	10	17	79
	-0.8	8	13	58
	-0.9	6	9	53
	-1.0	4	6	28
	-1.1	4	7	20
ALUMINUM	-0.8	8	1	49
	-0.9	3	6	26
	-1.0	2	4	28
	-1.1	1	2	11
MILD STEEL	-0.8	4	8	64
	-0.9	4	8	71
	-1.0	7	9	20
	-1.1	38	59	134
ALL ALLOYS	-0.6	13	21	110
	-0.7	11	16	83
	-0.8	7	11	65
	-0.9	5	8	47
	-1.0	5	7	31
	-1.1	13	20	45

TABLE III

Average Current Densities

METAL	POTENTIAL	AVERAGE CURRENT DENSITY (mA/m^2)			
	(volt)	50 days	100 days	800 days	12 weeks
ALUMINUM BRONZE	-0.6	340	270	160	140
	-0.7	240	180	90	60
	-0.8	160	140	90	90
	-0.9	110	90	90	90
	-1.0	90	80	60	70
	-1.1	160	120	30	20
BRASS	-0.6	250	200	140	100
	-0.7	200	150	100	80
	-0.8	190	160	100	70
	-0.9	190	140	60	40
	-1.0	170	130	60	50
	-1.1	100	80	40	30
COPPER	-0.6	290	240	120	100
	-0.7	220	170	100	80
	-0.8	130	110	80	60
	-0.9	110	90	70	80
	-1.0	80	70	50	40
	-1.1	180	120	26	10
90/10 COPPER/NICKEL	-0.6	280	210	190	90
	-0.7	240	170	120	110
	-0.8	110	90	60	60
	-0.9	80	70	60	60
	-1.0	100	70	40	30
	-1.1	200	140	40	20
70/30 COPPER NICKEL	-0.6	270	180	110	70
	-0.7	240	170	120	100
	-0.8	100	80	90	90
	-0.9	70	60	70	90
	-1.0	100	70	30	20
	-1.1	250	170	40	10

TABLE III
(cont)

Average Current Densities

METAL	POTENTIAL	AVERAGE CURRENT DENSITY (mA/m^2)			
	(volt)	50 days	100 days	800 days	12 weeks
MONEL	-0.6	270	150	150	150
	-0.7	220	170	110	80
	-0.8	120	90	80	60
	-0.9	80	60	90	120
	-1.0	120	80	30	10
	-1.1	530	460	110	40
316 STAINLESS STEEL	-0.6	260	200	130	90
	-0.7	240	190	90	80
	-0.8	190	140	80	80
	-0.9	130	90	40	50
	-1.0	110	80	30	20
	-1.1	360	270	60	20
TITANIUM	-0.6	220	180	150	110
	-0.7	210	170	100	60
	-0.8	170	130	70	50
	-0.9	120	90	70	60
	-1.0	80	60	40	30
	-1.1	100	70	20	20
MILD STEEL	-0.8	80	90	80	70
	-0.9	90	90	90	90
	-1.0	150	100	30	10
	-1.1	780	600	170	60
ALUMINUM	-0.8	170	140	60	30
	-0.9	70	70	20	10
	-1.0	50	50	40	20
	-1.1	30	20	10	10
ALL ALLOYS	-0.6			135	110
	-0.7			100	80
	-0.8			80	70
	-0.9			60	70
	-1.0			40	30
	-1.1			55	20

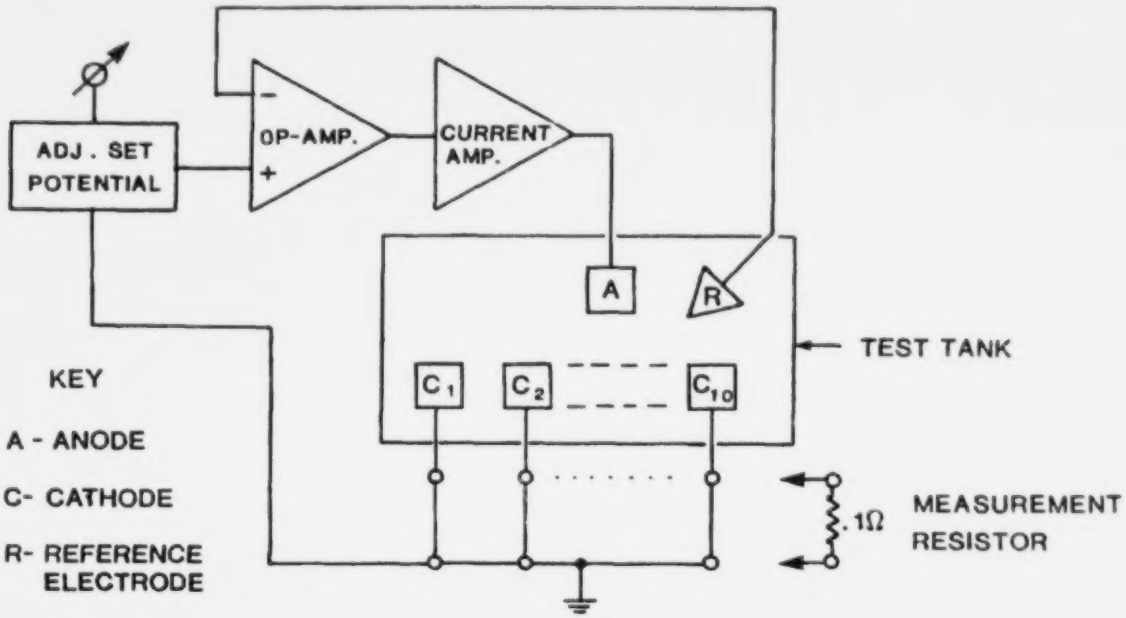

Figure 1. Original DREP Potentiostatic Circuit (Simplified Schematic).

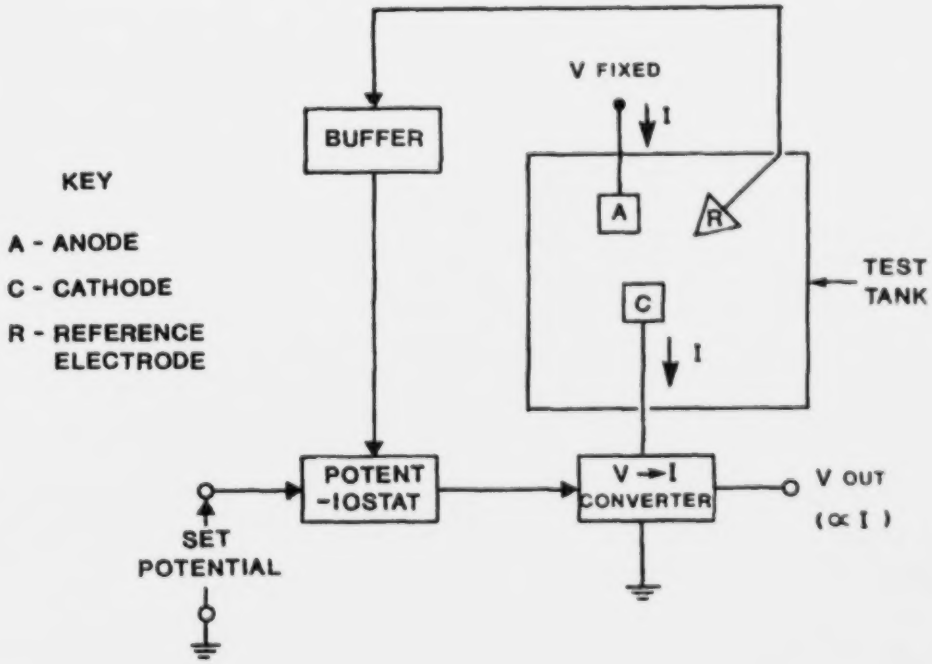

Figure 2. Block Diagram of New DREP Potentiostatic Circuit (Canada, USA Patent Pending.

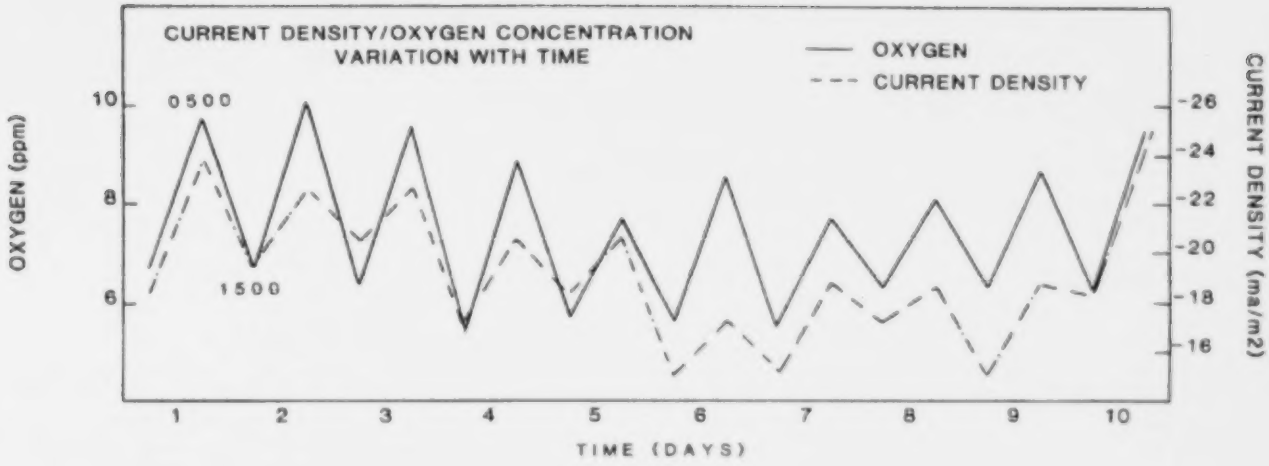

Figure 3. Variation of Current Density and Oxygen Concentration With Time.

Figure 4. Fouling after 800 Days on a Copper Panel at -1.0V.

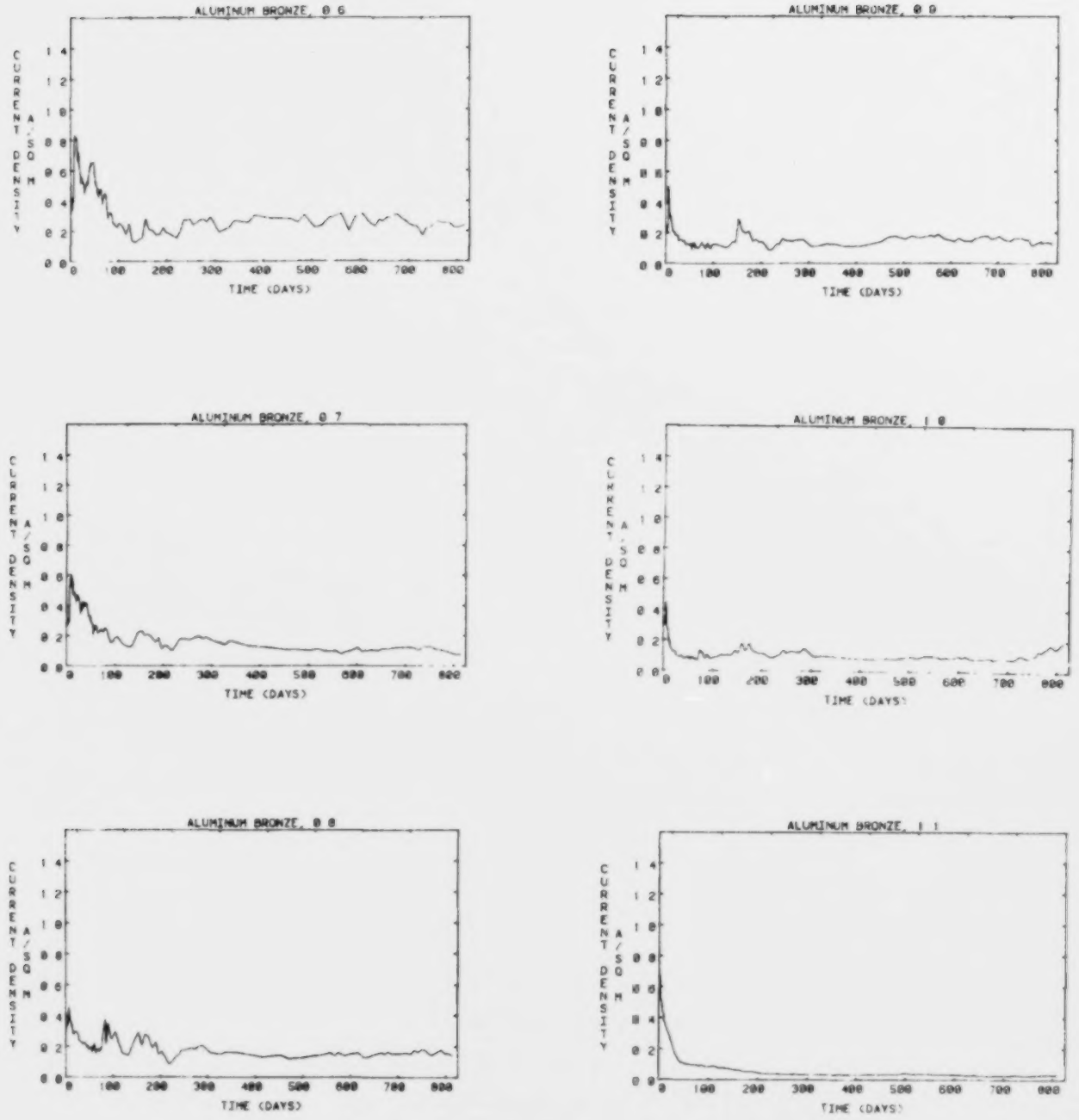

Figure 5. Plot of Current Density Versus Time for Aluminum-Bronze at Potentials of -0.6V to -1.1V.

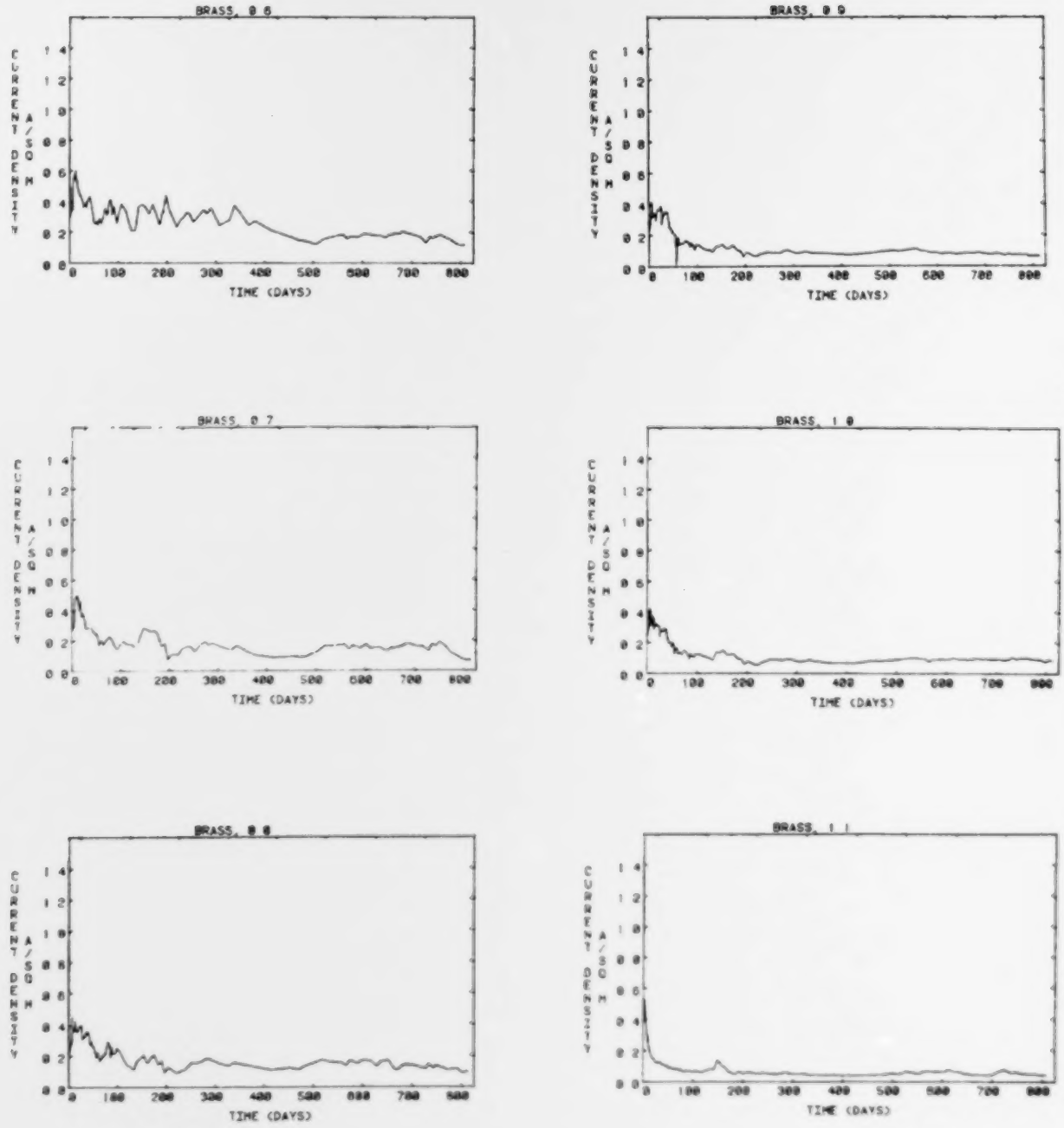

Figure 6. Plot of Current Density Versus Time for Brass at Potentials of -0.6V to -1.1V.

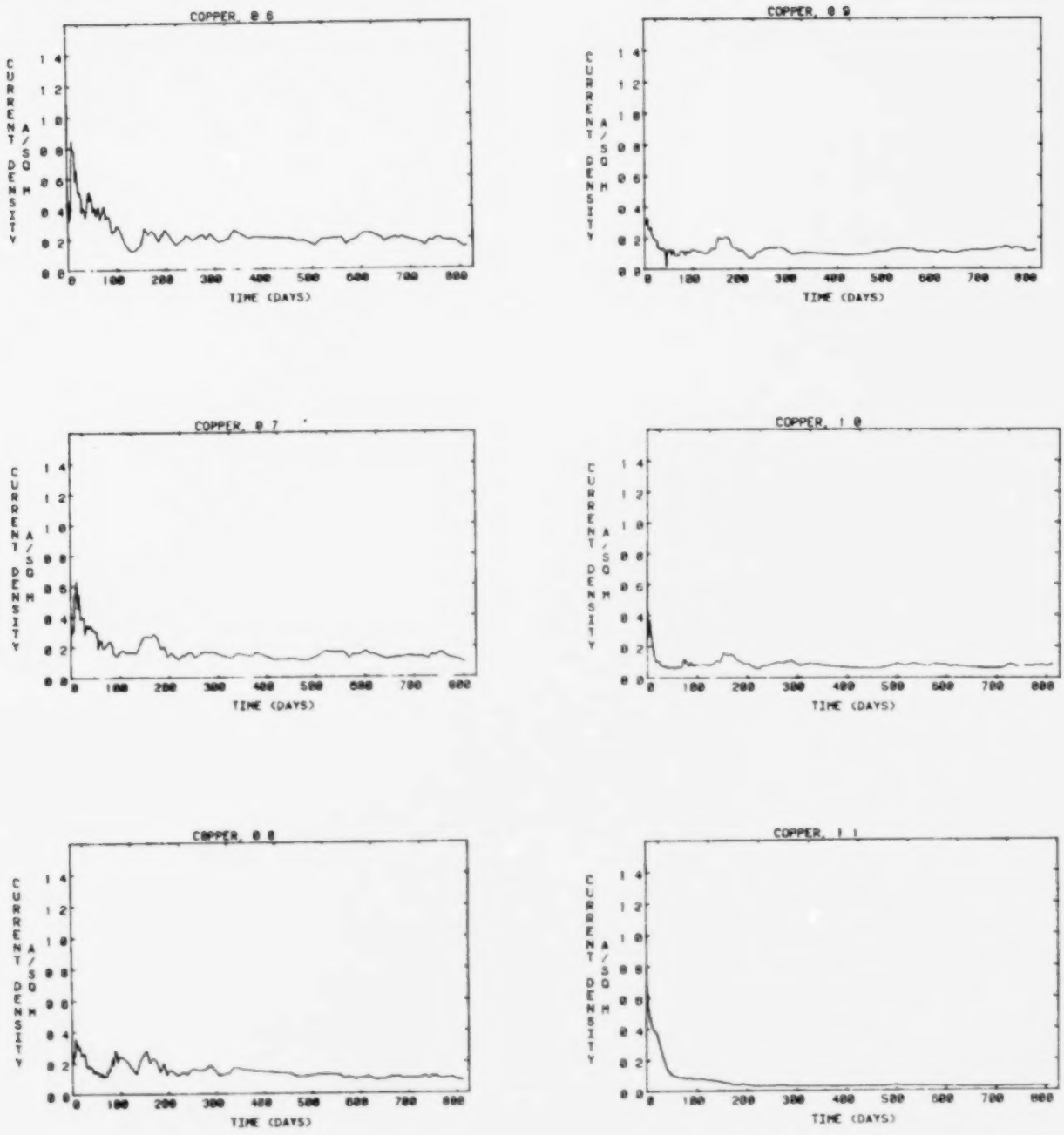

Figure 7. Plot of Current Density Versus Time for Copper at Potentials of -0.6V to -1.1V.

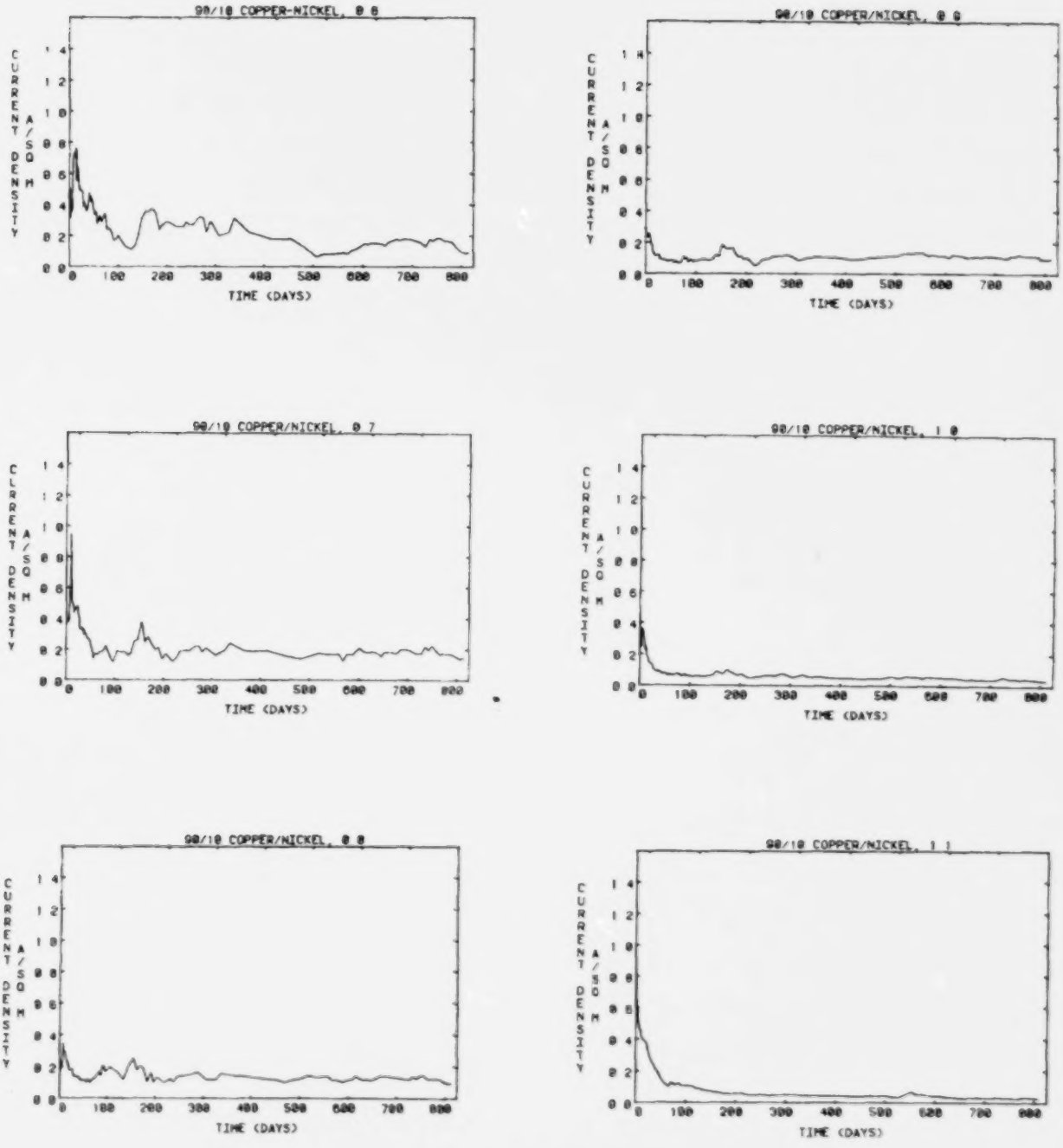

Figure 8. Plot of Current Density Versus Time for 90/10 Copper/Nickel at Potentials of -0.6V to -1.1V.

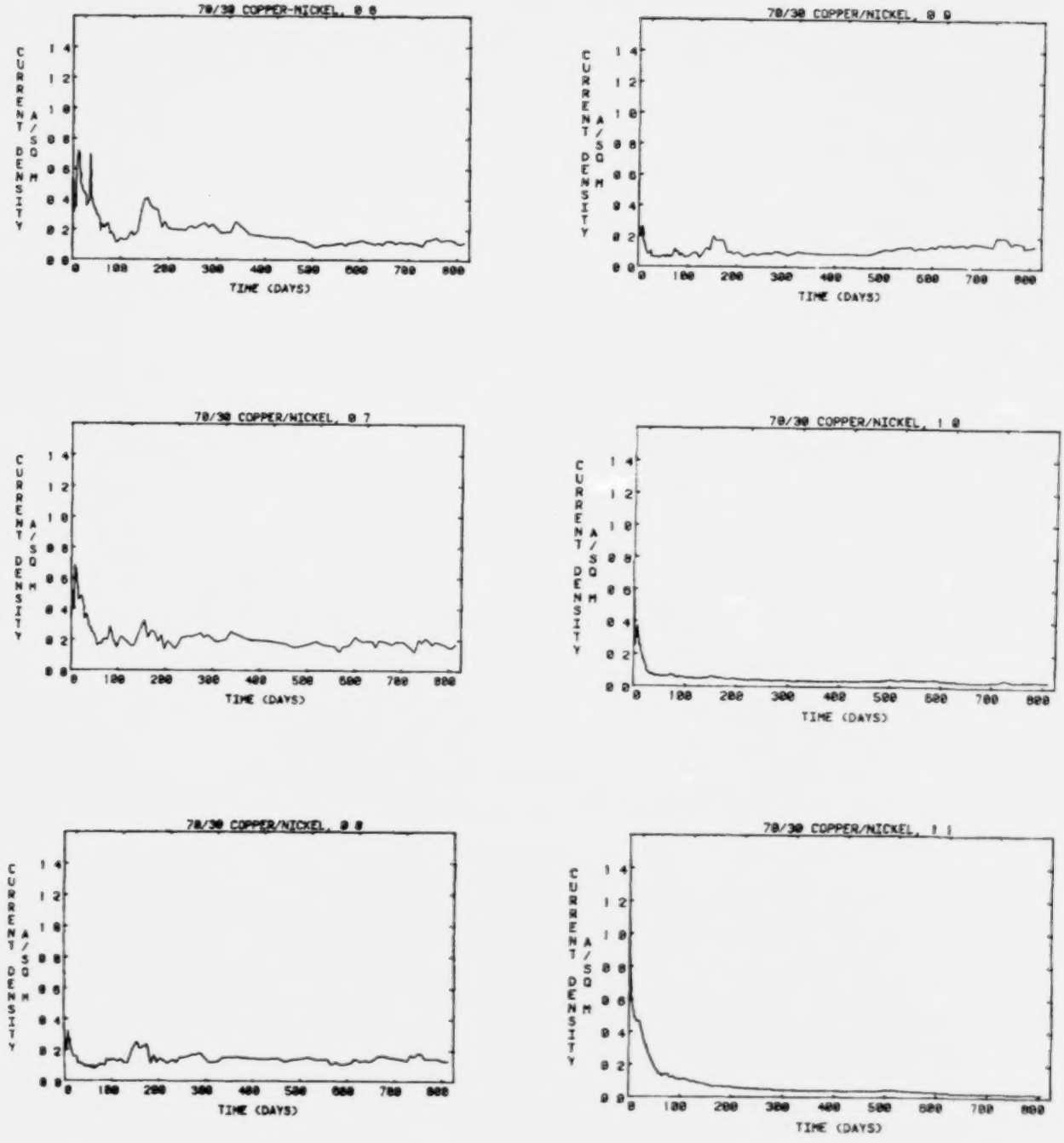

Figure 9. Plot of Current Density Versus Time for 70/30 Copper/Nickel at Potentials of -0.6V to -1.1V.

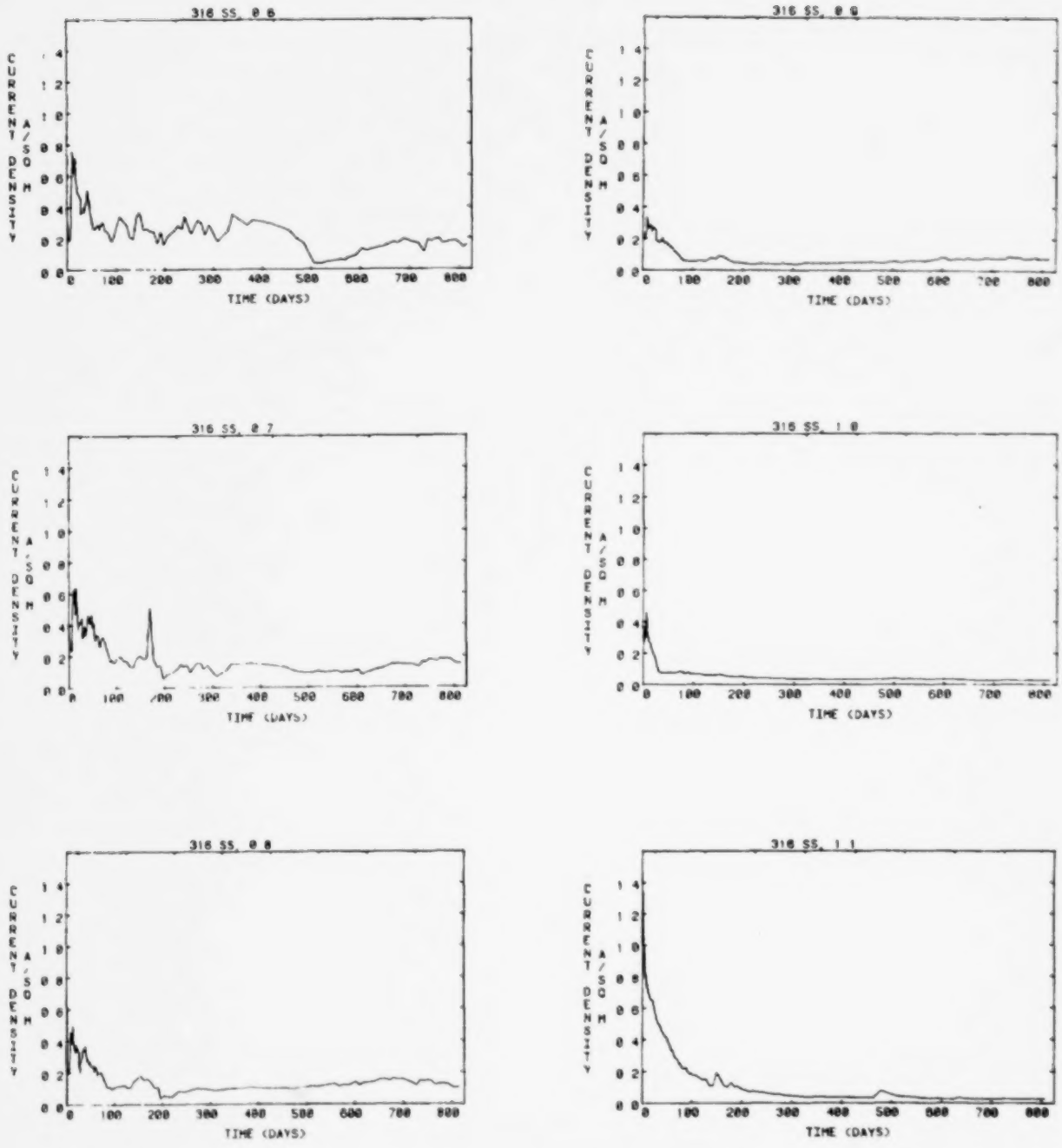

Figure 10. Plot of Current Density Versus Time for 316 Stainless Steel at Potentials of -0.6V to -1.1V.

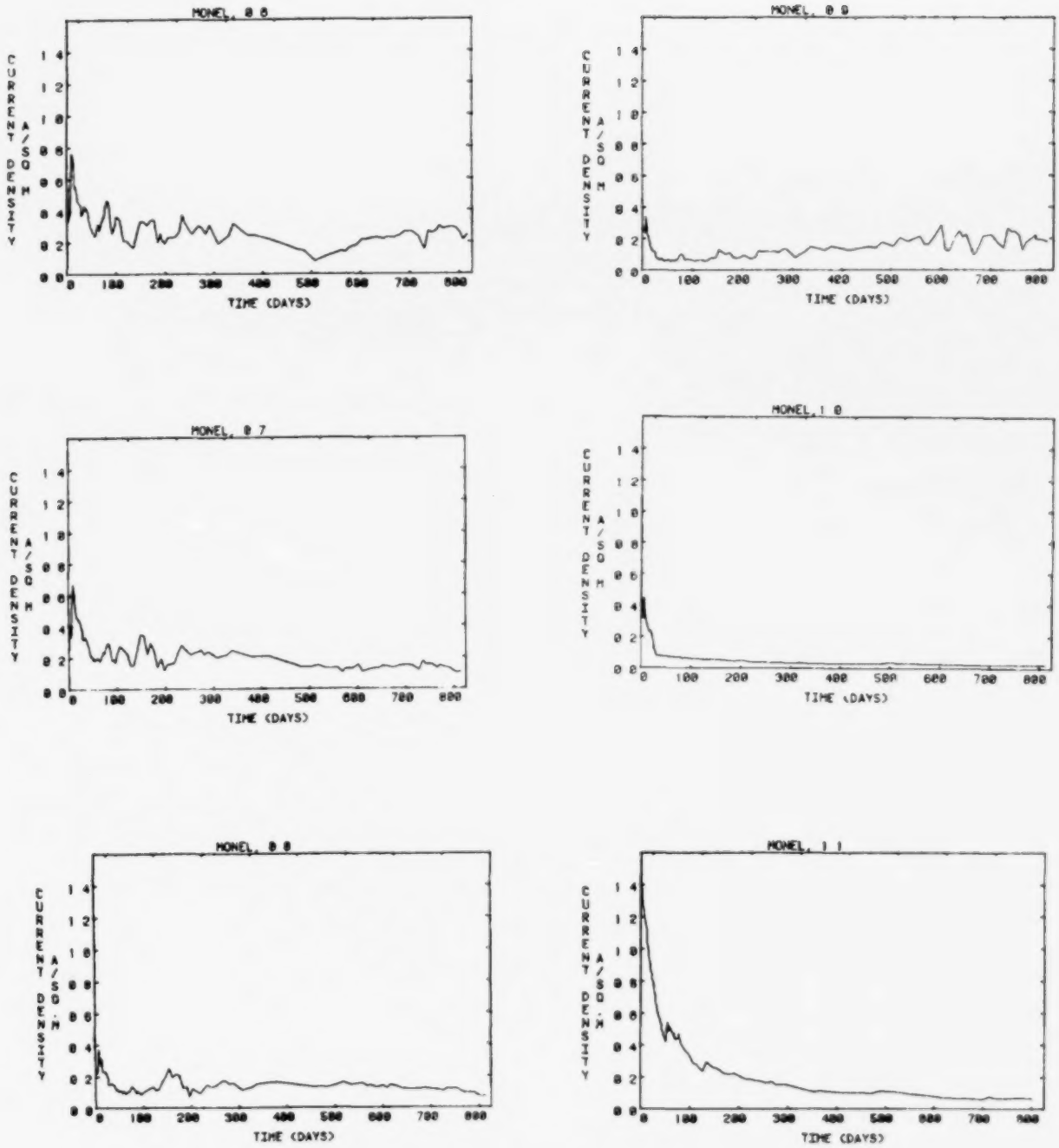

Figure 11. Plot of Current Density Versus Time for Monel at Potentials of -0.6V to -1.1V.

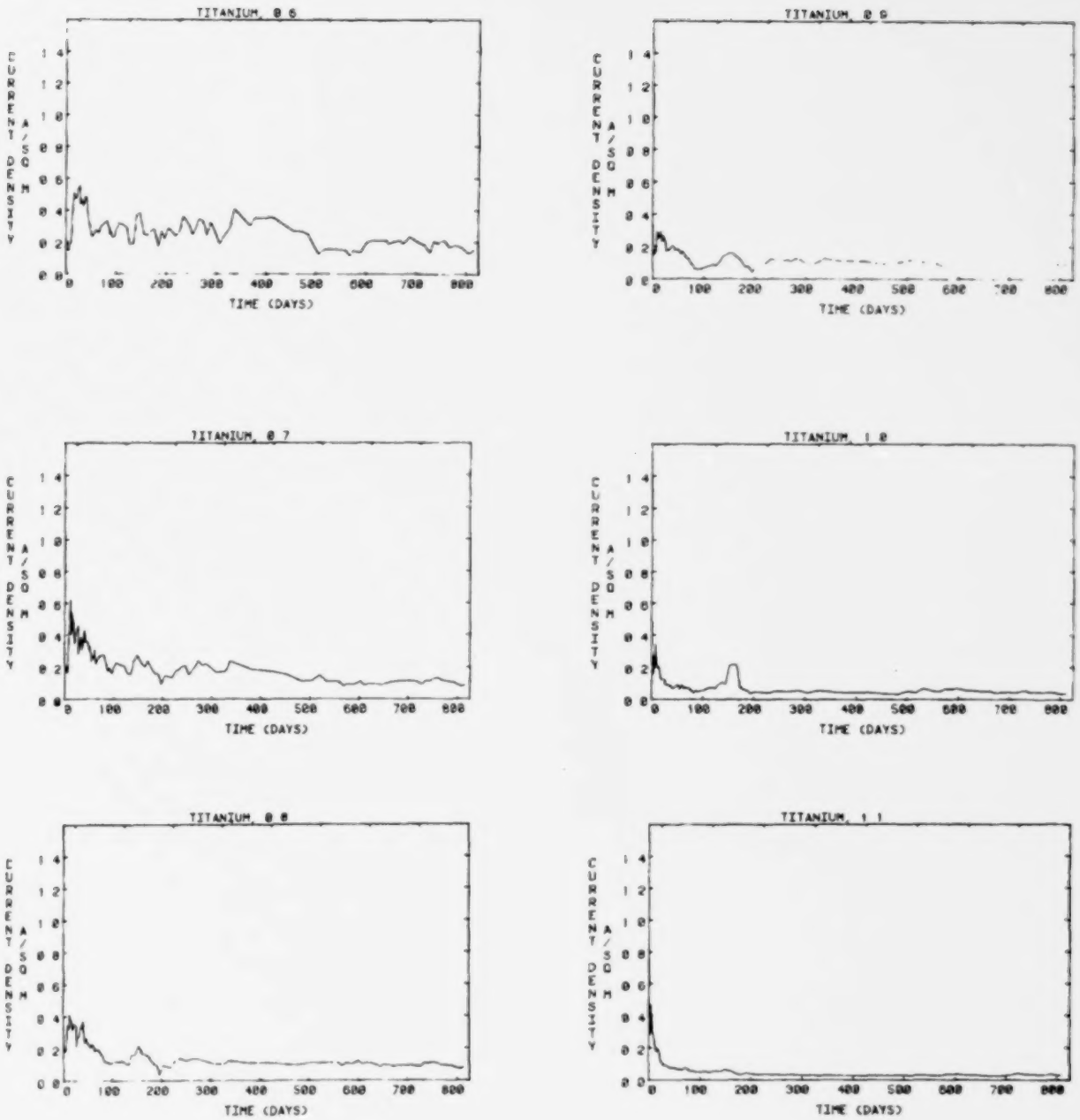

Figure 12. Plot of Current Density Versus Time for Titanium at Potentials of -0.6V to -1.1V.

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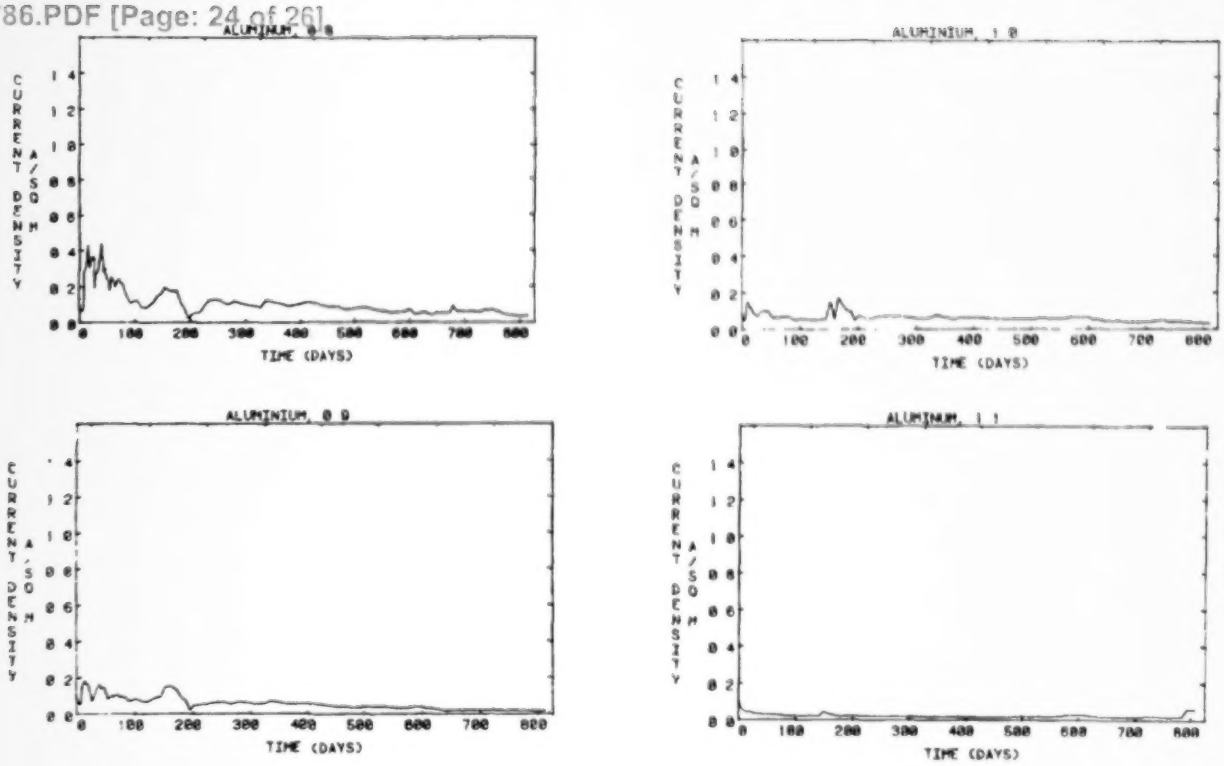

Figure 13. Plot of Current Density Versus Time for Aluminum at Potentials of -0.6V to -1.1V.

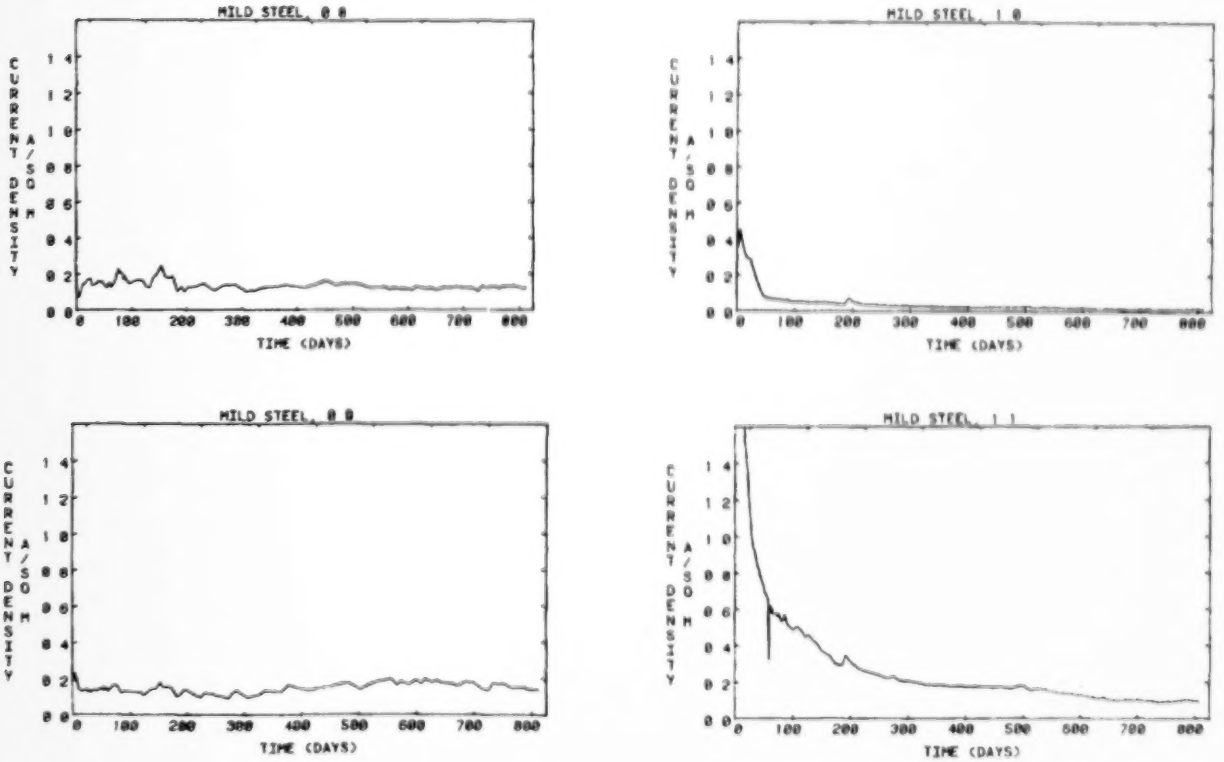

Figure 14. Plot of Current Density Versus Time for Mild Steel at Potentials of -0.6V to -1.1V.

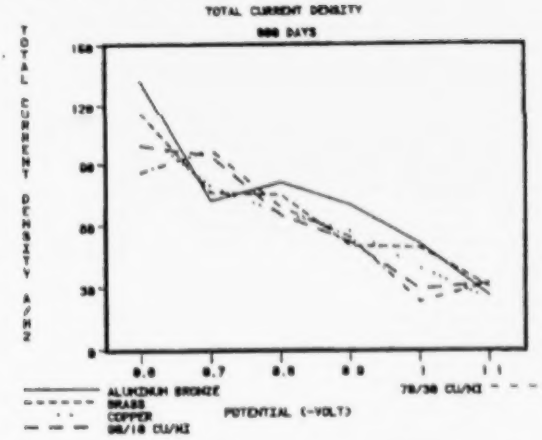

Figure 15. Plot of Total Current Requirement Versus Potential for Copper Based Alloys.

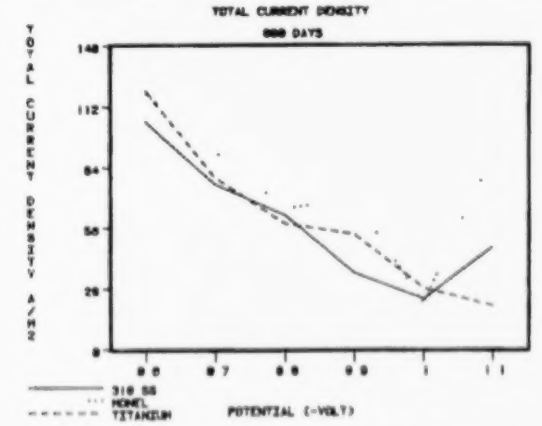

Figure 16. Plot of Total Current Requirement Versus Potential for Stainless Steel, Monel, and Titanium.

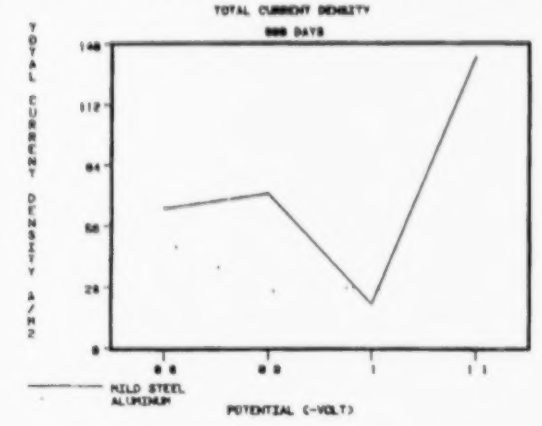

Figure 17. Plot of Total Current Requirement Versus Potential for Mild Steel and Aluminum.

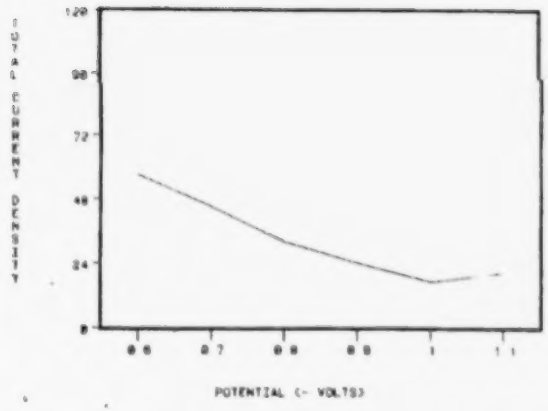

Figure 18. Plot of Total Current Requirement Versus Potential for All Alloys.

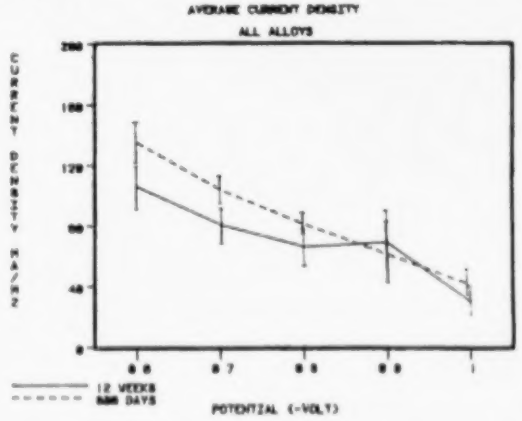

Figure 19. Plot of Average Density for Alloys at Potentials Between -0.6V and -1.9V for the Final 12 Weeks and Over the 800-Day Test.